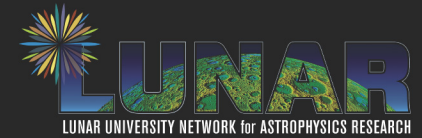


N A S A  
LUNAR SCIENCE  
I N S T I T U T E

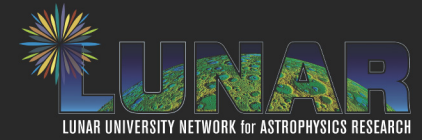
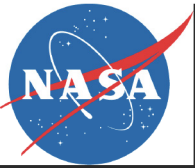


# The Moon as a Science Platform

Joseph Lazio

(Jet Propulsion Laboratory, California Institute of Technology),  
J. Bowman (ASU), J. O. Burns (U. Colorado), W. M. Farrell (NASA/GSFC),  
D. L. Jones (JPL/CIT), J. Kasper (CfA),  
R. MacDowall (NASA/GSFC), K. P. Stewart (NRL), K. Weiler (NRL)  
&  
NASA Lunar Science Institute

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Government sponsorship acknowledged.



# Why The Moon?

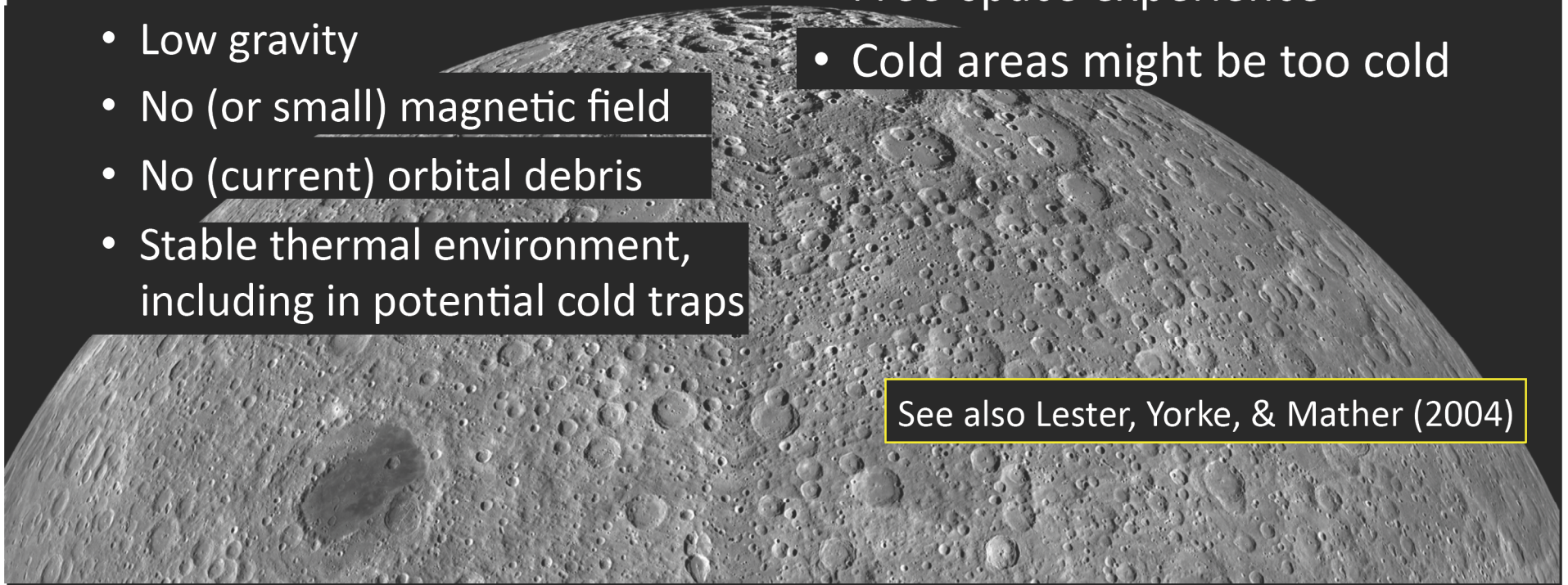
## Advantages

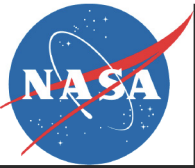
- No atmosphere
- Tidally locked
- Seismically stable
- Low gravity
- No (or small) magnetic field
- No (current) orbital debris
- Stable thermal environment, including in potential cold traps

## Disadvantages

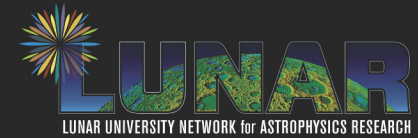
- Dust
- Non-zero gravity
- Free-space experience
- Cold areas might be too cold

See also Lester, Yorke, & Mather (2004)





# Lunar University Network for Astrophysics Research (LUNAR)



## Astrophysics & Cosmology

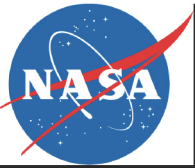
Track the evolution of the Universe through the Dark Ages and into the Epoch of Reionization via the highly redshifted 21 cm hyperfine spin-flip line from neutral hydrogen

- Secondary science goals:
  - Magnetospheric emissions from extrasolar planets
  - Radio transients
- Why the Moon?
  - Tidally locked—far-side is radio quiet
  - No atmosphere

## Heliophysics

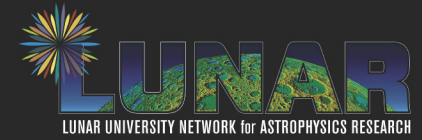
Determine the sites and mechanisms for particle acceleration in the inner heliosphere.

- Secondary science goals:
  - Interplanetary dust
- Why the Moon?
  - No atmosphere



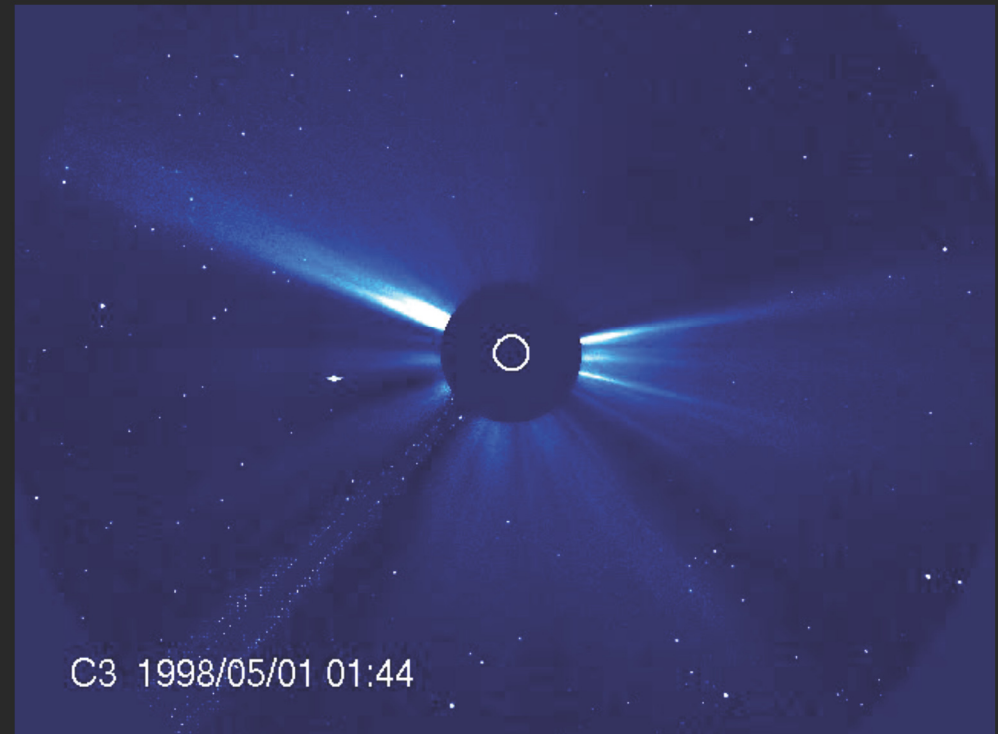
# Radio Heliophysics

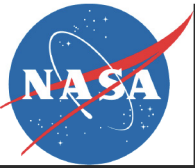
## Space Weather



Coronal mass ejections (CMEs) emit large quantities of magnetized plasma into inner solar system

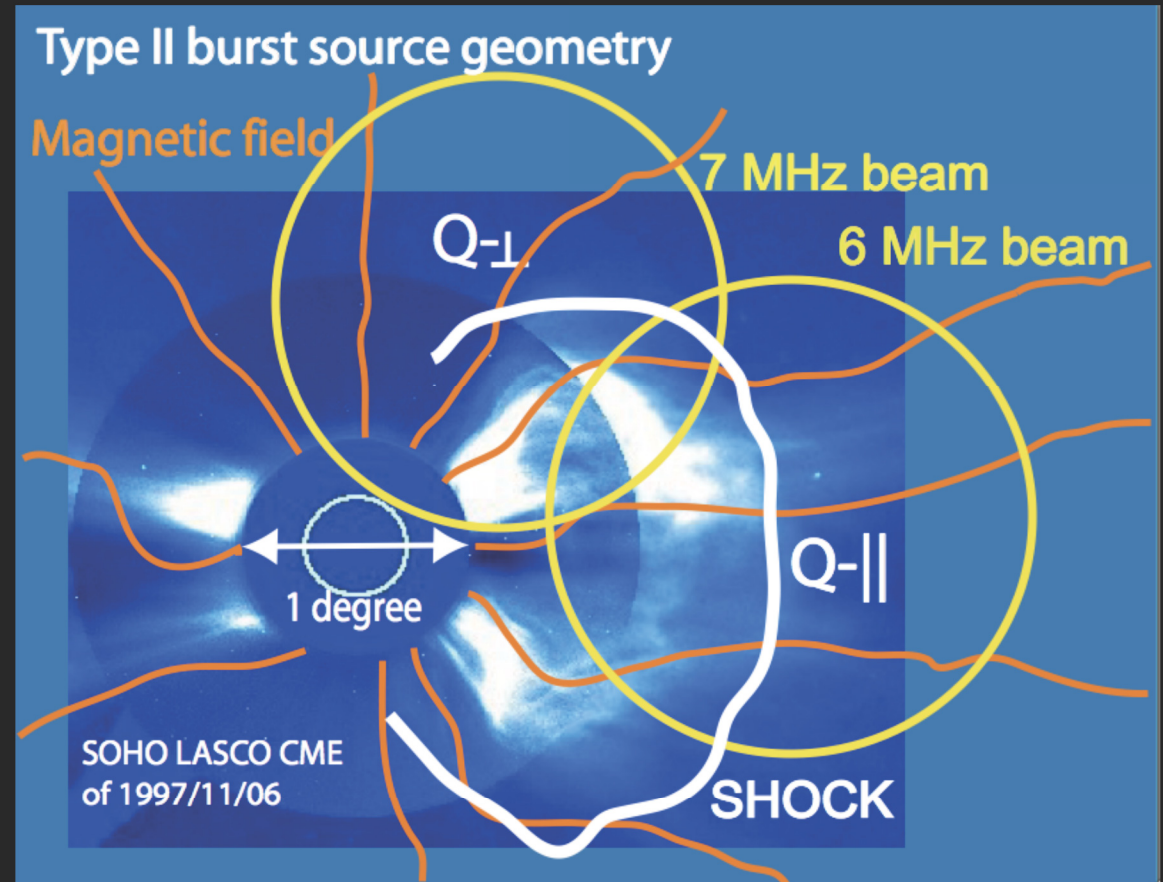
- Accelerate particles
  - How?
  - Where?
  - Relevance to larger (astro-) physical questions
- Can affect space systems and infrastructure
  - E.g., Quebec power grid failure of 1989
- Can affect astronaut health

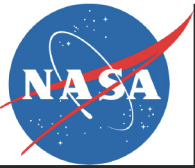




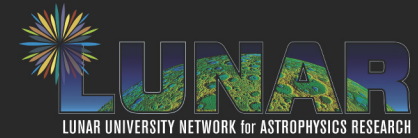
# Radio Heliophysics

- What are mechanisms and sites of particle acceleration?
- How do CME interactions produce solar energetic particle (SEP) events?
- Need imaging
  - ... though considerable progress to date via dynamic spectra



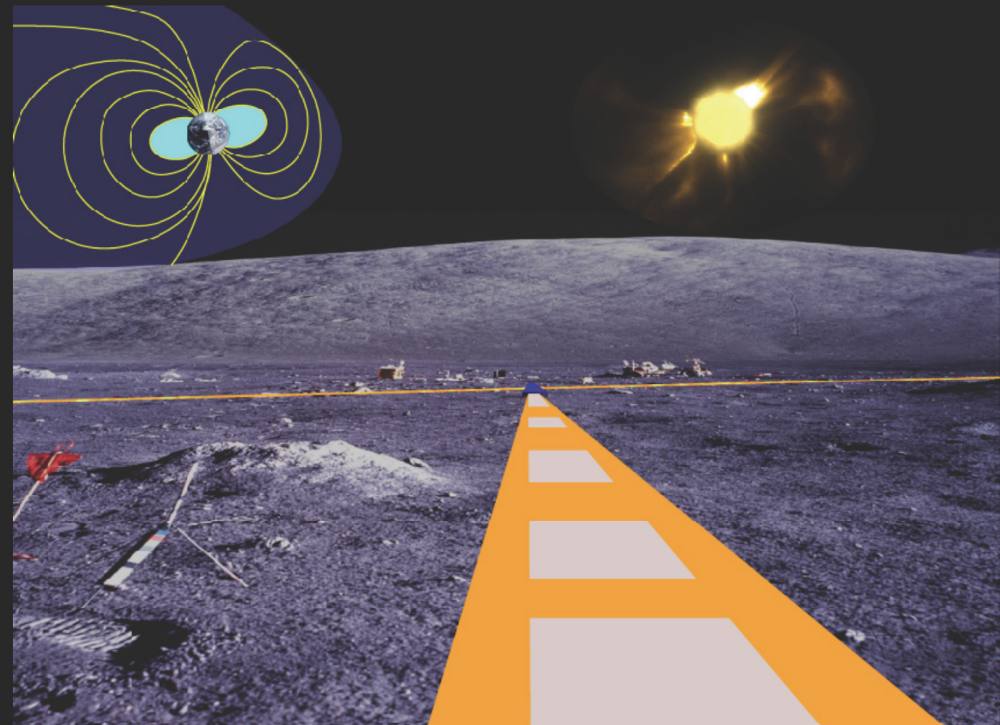


# Radio Observatory on the Lunar Surface for Solar Studies (ROLSS)

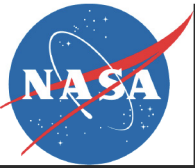


Imaging instrument capable of  $2^\circ$  resolution @ 30 m wavelength

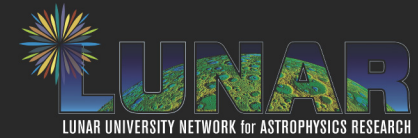
- 30–300 m wavelength (1–10 MHz frequency)
  - Relevant range for particle acceleration
  - Upper range for lunar ionosphere
  - Inaccessible from the ground
- 3-arm interferometer
  - 500 m long arms
  - First imaging instrument at these wavelengths
  - Order of magnitude improvement in resolution at these wavelengths



Lazio et al. (2011, *Adv. Space Res.*, **48**, 1942)



# Lunar University Network for Astrophysics Research (LUNAR)



## Astrophysics & Cosmology

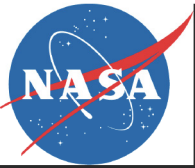
Track the evolution of the Universe through the Dark Ages and into the Epoch of Reionization via the highly redshifted 21 cm hyperfine spin-flip line from neutral hydrogen

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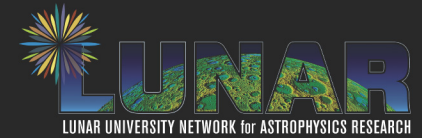
## Heliophysics

Determine the sites and mechanisms for particle acceleration in the inner heliosphere.

- Secondary science goals:
  - Interplanetary dust
- Why the Moon?
  - No atmosphere



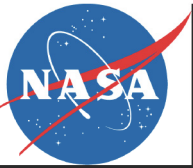
# Cosmic Dawn and the Dark Ages



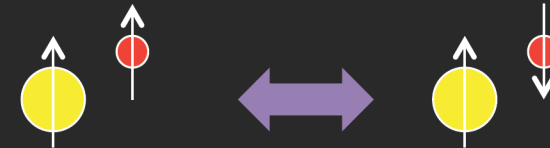
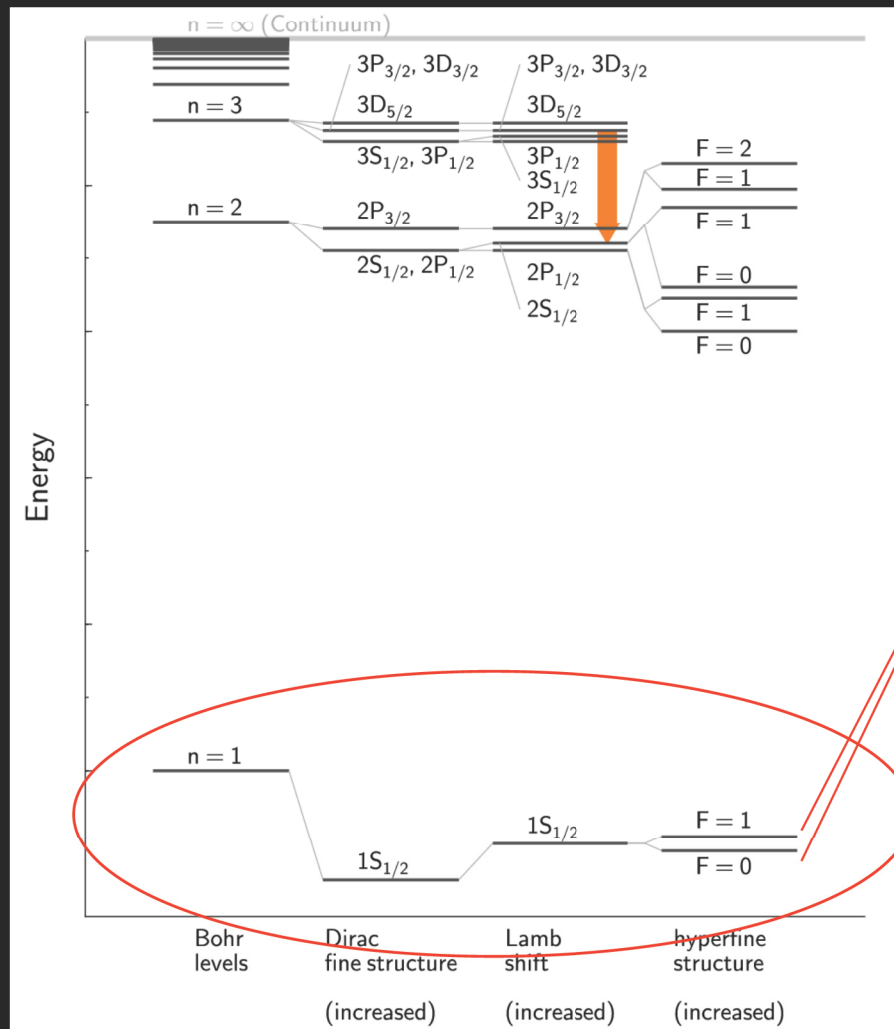
*“What were the first objects to light up the Universe and when did they do?”*

New Worlds, New Horizons in  
Astronomy & Astrophysics  
Cf. European AstroNet





# Hydrogen Atom



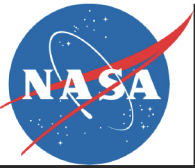
$$n = 1, F = 1 \rightarrow 0$$

$$E_{10} = h\nu = 5.8743253 \mu\text{eV}$$

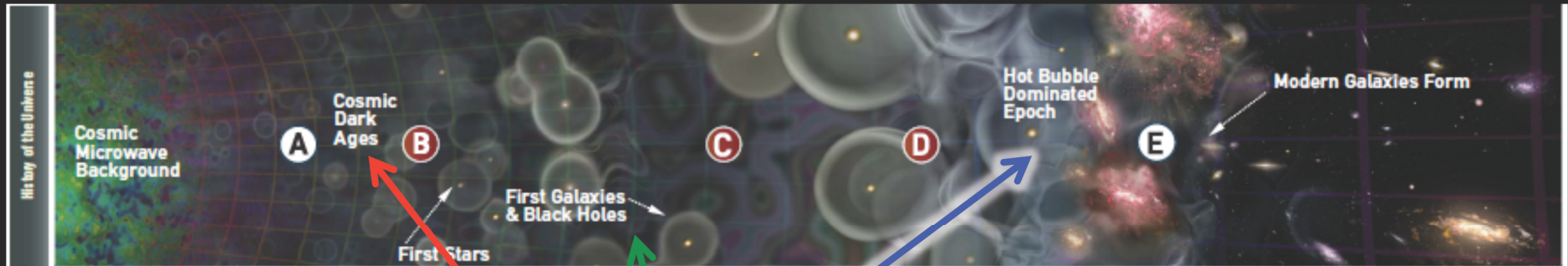
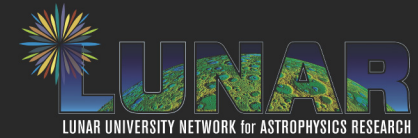
$$T_* = E_{10}/k = 0.068 \text{ K}$$

$$\nu = 1420.405752 \text{ MHz}$$

$$\lambda = 21 \text{ cm}$$



# Cosmic Dawn and Dark Ages Hydrogen Signal



## Neutral Hydrogen

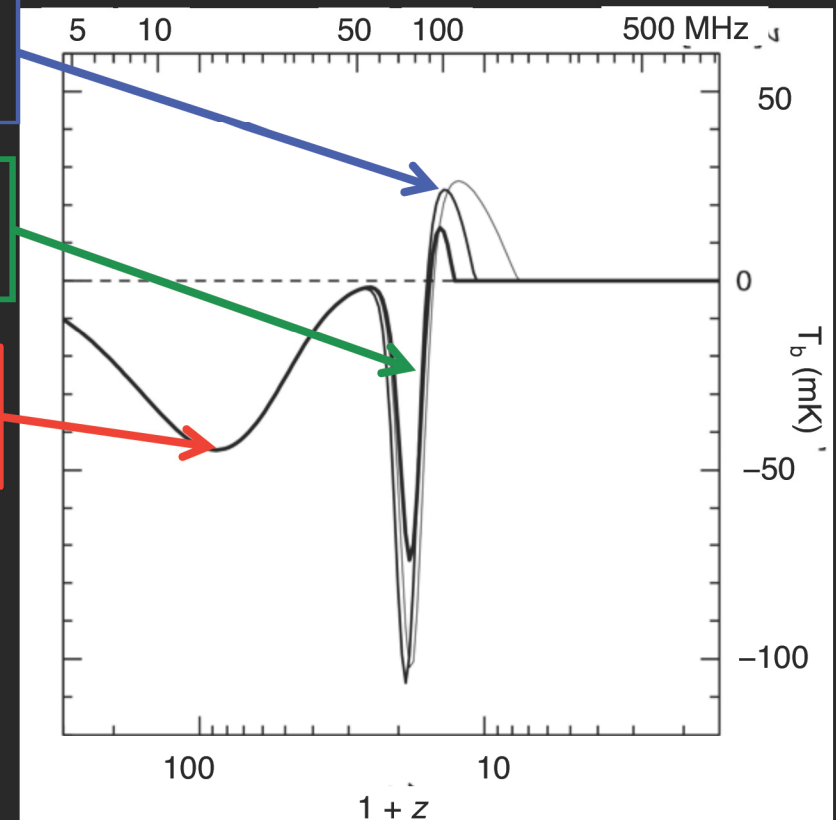
Spin-flip transition provides probe of neutral intergalactic medium before and during formation of first stars

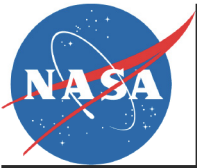
EoR

Cosmic Dawn

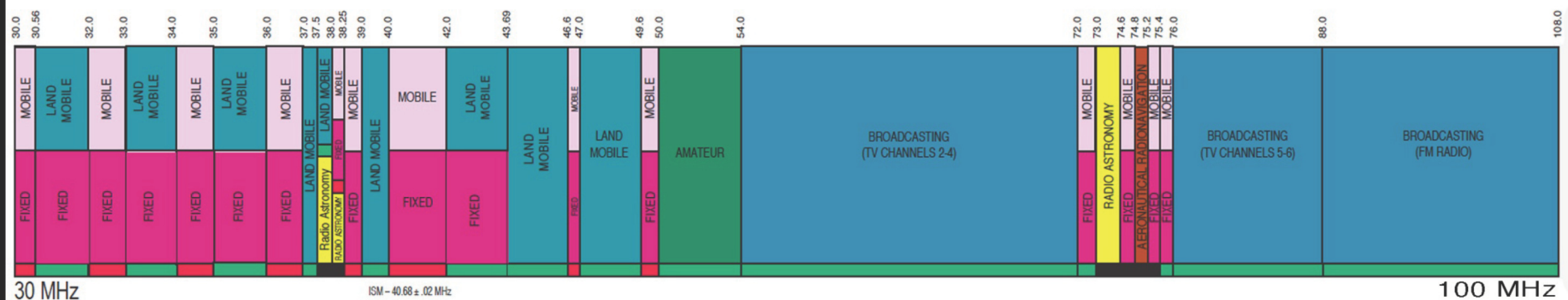
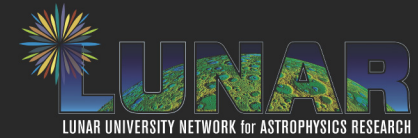
Dark Ages

$$\nu = 1420 \text{ MHz}/(1 + z)$$
$$\lambda = 21 \text{ cm } (1 + z)$$





# Radio Spectrum



50 Myr  
since Big  
Bang

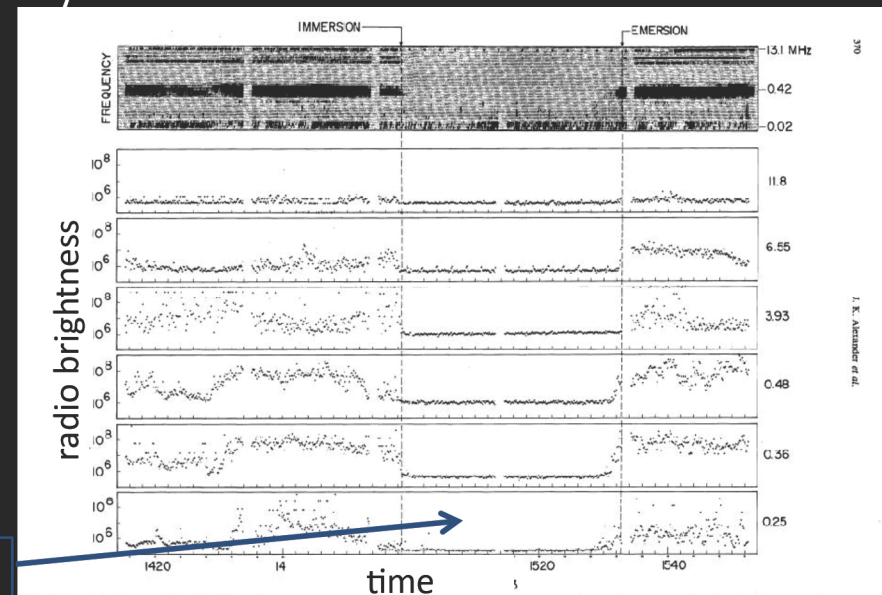
Portion of radio spectrum relevant for 21 cm observations of  
Cosmic Dawn and Dark Ages

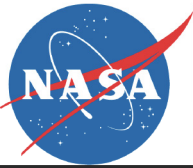
330 Myr  
since Big  
Bang

- Yellow = reserved for radio astronomy

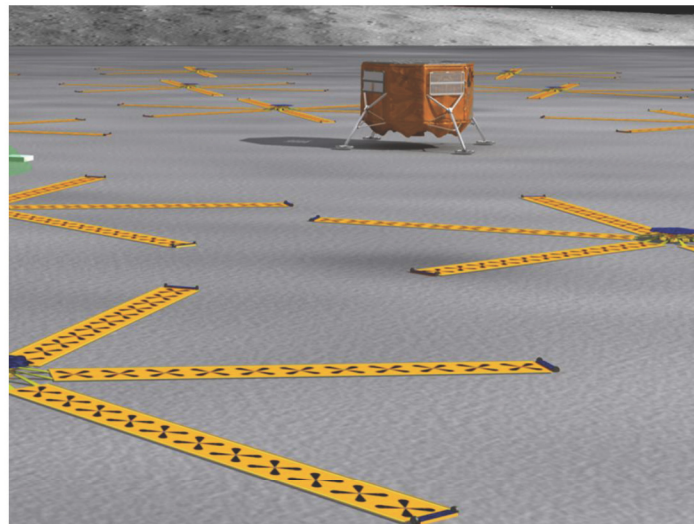
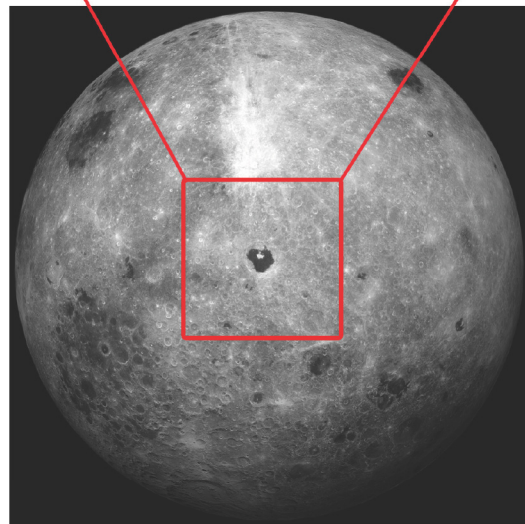
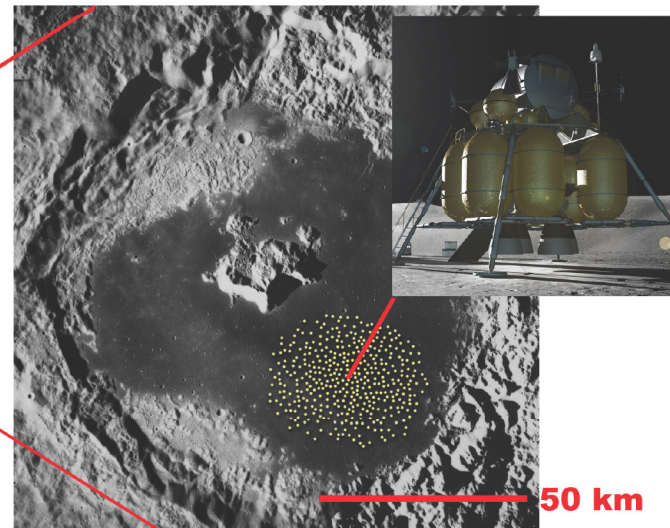
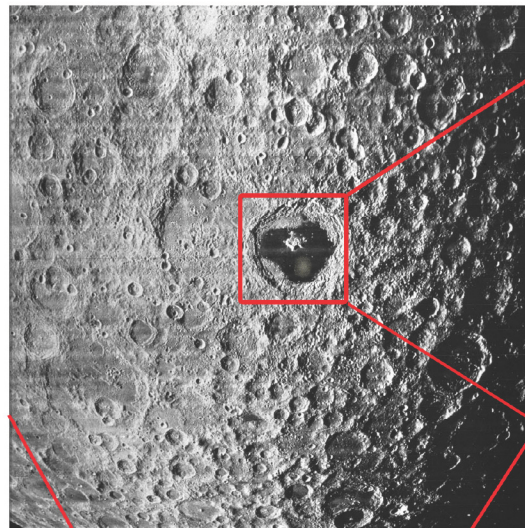
- Data from Radio Astronomy Explorer-2, when it passed behind the Moon, illustrating cessation of terrestrial emissions
- *Apollo* command modules lost communications when behind the Moon.

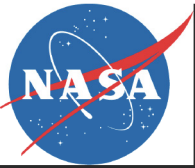
RAE-2 behind Moon



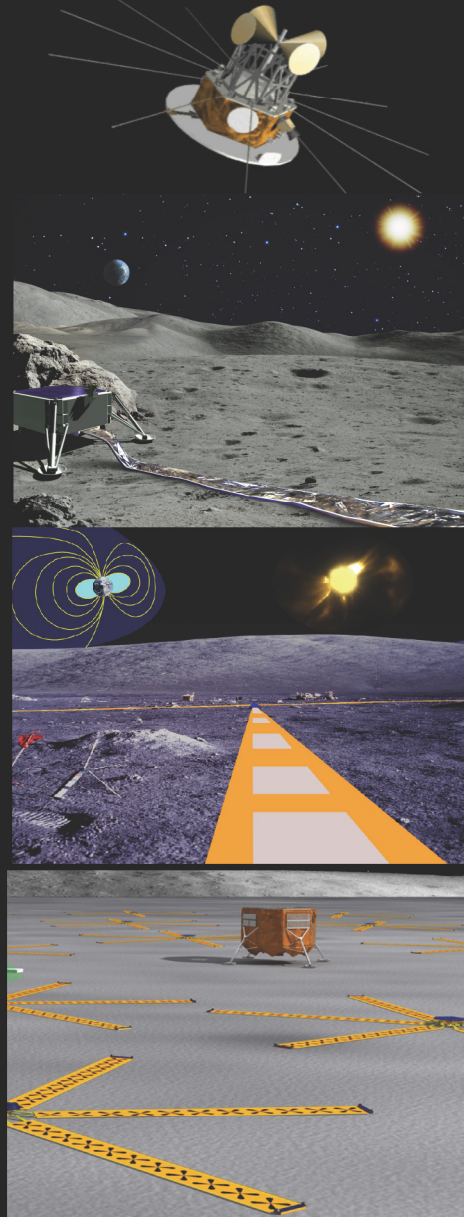
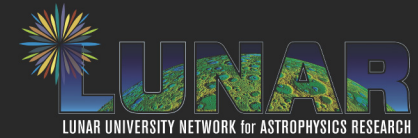


# Lunar Radio Array

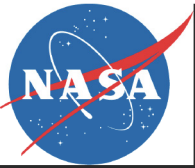




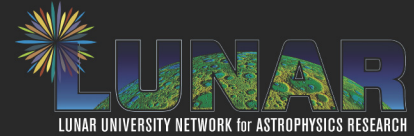
# Roadmap



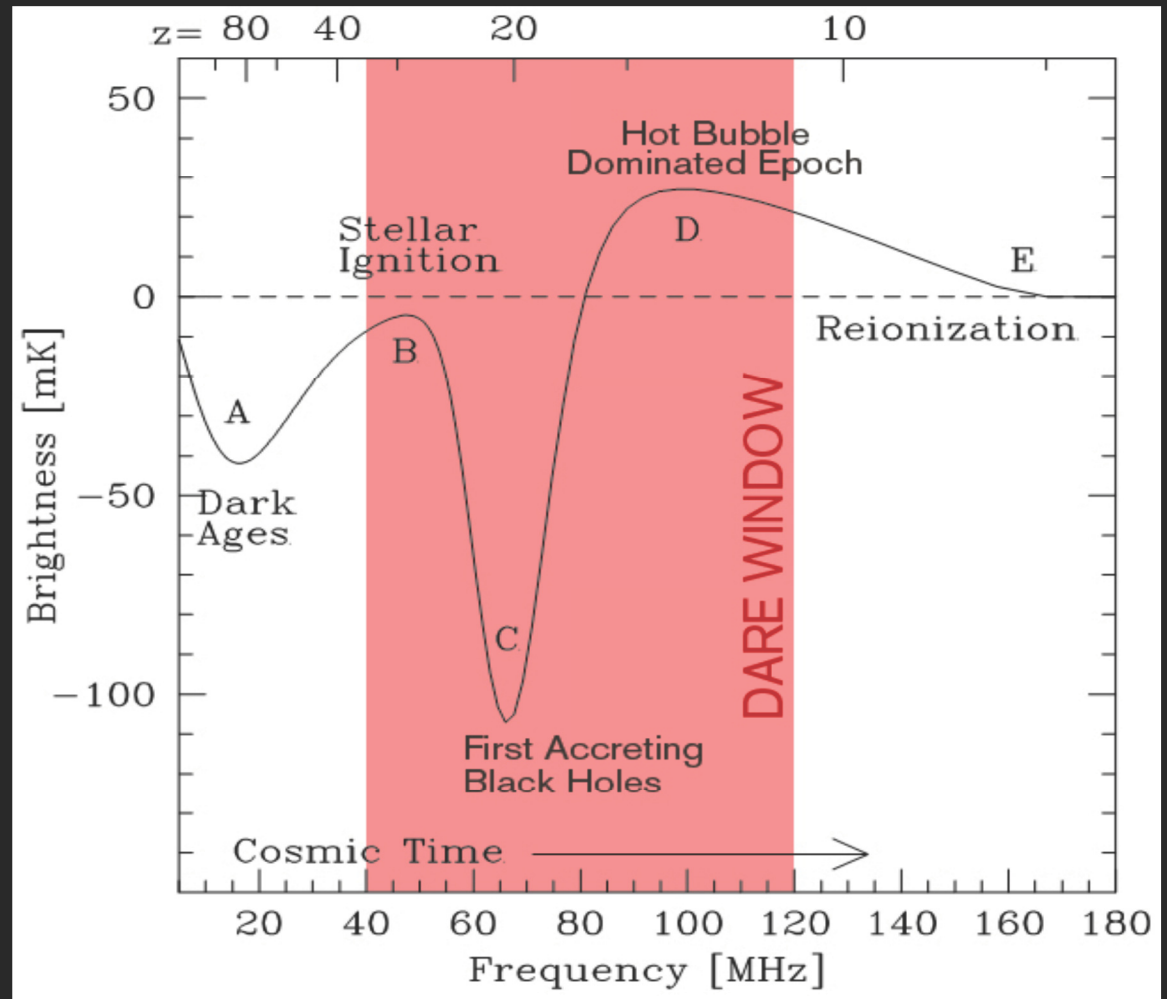
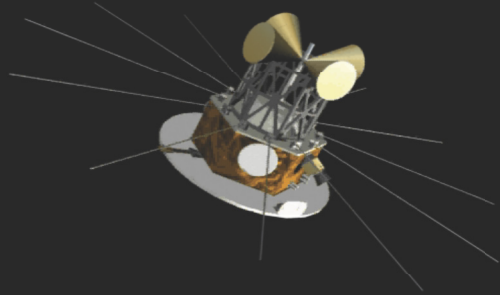
- I. Dark Ages Radio Explorer  
Lunar orbiter
- II. 1 (or few) antennas on Moon
  - Lunar Atmosphere Probe Station
  - Study lunar ionosphere, radio environment
- III.  $\sim 100$  antennas
  - Solar and heliophysics studies
  - Near or far side
  - Radio Observatory on the Lunar Surface for Solar Studies
- IV.  $> 10^4$  antennas
  - Cosmology and astrophysics
  - Far side
  - Lunar Radio Array

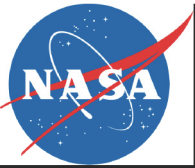


# Dark Ages Radio Explorer



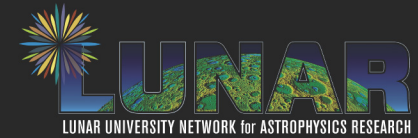
- DARE carries a single, high-heritage instrument operating at 40-120 MHz
- Components of all three subsystems (antenna, receiver and spectrometer) are at TRL  $\geq 6$
- Work underway to have the integrated instrument at TRL 6



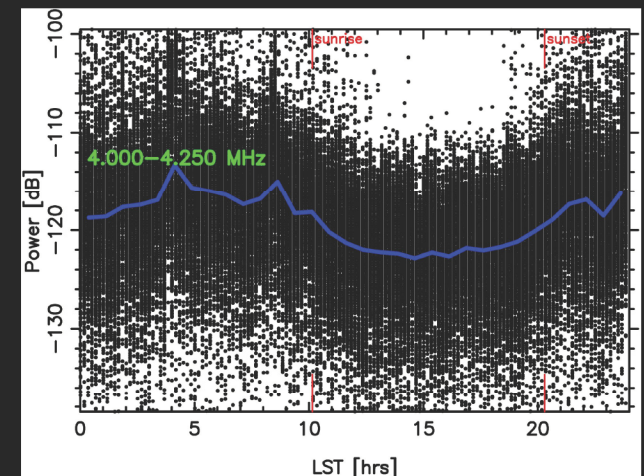
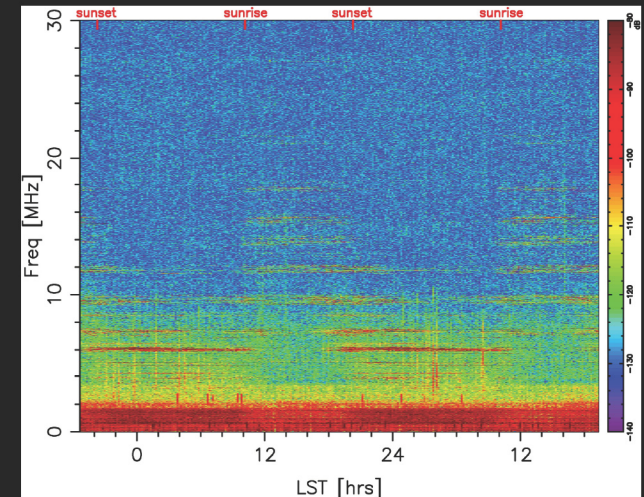


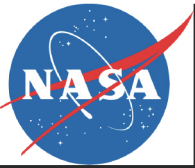
# Polyimide Film Antenna

## Field Tests

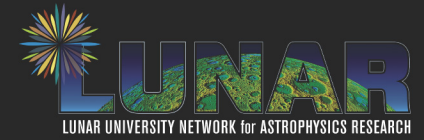


- 5  $\mu\text{m}$  thick Cu layer deposited on 25  $\mu\text{m}$  thick Kapton
- Dipole arm was 8 m long and 30.5 cm wide
- Inner 1 m of each arm tapered to a point at which a 1:1 wideband balun attached
- Good agreement with models (*not shown*)
- Spectrum recorded from 1–30 MHz every 10 min for just over 2 days
- Local noon occurred at LST  $\sim 15$  hrs
- Decrease in power below 7 MHz is due to absorption by the D layer of the ionosphere





# Summary



## The Moon as a Science Platform

- Moon offers valuable platform for space sciences studies
  - No atmosphere
  - Farside is radio quiet
- Compelling science program
  - Cosmic Dawn and the Dark Ages
  - Particle acceleration and space weather
- Technology and engineering development making good progress
- Staged roadmap with science and technology development at every step

